

Jamming Energy Allocation in Training-Based Multiple Access Systems

Hamed Pezeshki, *Student Member, IEEE*, Xiangyun Zhou, *Member, IEEE*,
and Behrouz Maham, *Member, IEEE*

Abstract—We consider the problem of jamming attack in a multiple access channel with training-based transmission. First, we derive upper and lower bounds on the maximum achievable ergodic sum-rate which explicitly shows the impact of jamming during both the training phase and the data transmission phase. Then, from the jammer's design perspective, we analytically find the optimal jamming energy allocation between the two phases that minimizes the derived bounds on the ergodic sum-rate. Numerical results demonstrate that the obtained optimal jamming design reduces the ergodic sum-rate of the legitimate users considerably in comparison to fixed power jamming.

Index Terms— jamming, training-based transmission, optimum energy allocation, multiple access channel.

I. INTRODUCTION

The problem of jamming exists in many practical wireless communication scenarios and can culminate in dissatisfactory Quality of Service (QoS) in commercial networks. For communication systems requiring training signals to facilitate channel estimation at the receiver, smart jamming attack during the training phase can result in a detrimental effect [1], [2]. Recently, optimal jamming energy allocation against training-based, single-user point-to-point systems was studied in [3], where the jammer optimally allocates its energy to attack both the training and data transmission phases. In this letter, we focus on a multiuser system over a multiple access channel (MAC) [4], [5] and design the jamming energy allocation from the attacker's perspective.

In the multiuser MAC setting, the jammer's design depends on the system parameters of *all* the users. For instance, the optimal power level for jamming a particular user's training signal depends not only on the training power of this user, but also on the power levels of all the other users in both training and data transmission. Hence, the jammer's design in the multiuser system is much more challenging compared with the single-user system because of the complex interdependence between a large number of parameters of all users.

To facilitate the smart jammer design, we first derive tractable upper and lower bounds on the ergodic sum-rate of the MAC system, taking into account the different jamming powers used during training and data transmission. Then, we find analytical solutions to the jamming energy allocation which minimizes the bounds on the ergodic sum-rate. Our

numerical results compare the ergodic sum-rate achieved under the optimal jamming energy allocation with that under fixed power jamming, i.e., the non-optimized case. A significant rate reduction from the non-optimized case to the optimized case is observed, ranging from 35% to 90%, which clearly shows the potential impact of smart jamming attack in training-based MAC systems.

II. SYSTEM MODEL

We consider a block-fading single-antenna narrowband multiple access channel (MAC) with K users. This structure forms the legitimate users of our model. We also assume that there exists a smart jammer which intends to reduce the ergodic sum-rate of the legitimate users by injecting an artificial noise. The input-output relationship of the legitimate users is given by

$$y = \sum_{k=1}^K h_k x_k + n + w \quad (1)$$

where x_k and y are the transmitted symbol by user k , $k \in \mathcal{K} = \{1, \dots, K\}$, and the received symbol, respectively. $h_k \sim \mathcal{CN}(0, 1)$ is the channel coefficient of user k , $n \sim \mathcal{CN}(0, 1)$ is the additive white Gaussian noise and finally w is the artificial noise injected by the jammer, which is again assumed to be Gaussian, since for Gaussian channels the Gaussian distribution is the best from the jammer's design point of view [6]. We have normalized the variances of h_k and n to one, without loss of generality.

We consider a training-based blockwise transmission, where each block in every user starts with a training phase followed by a data transmission phase. The training signals of the users are assumed to be non-overlapping in time [4], [5]¹. Each user sends T_{t_k} pilot symbols, therefore the total training duration is $T_t = \sum_{k=1}^K T_{t_k}$. During the training phase the receiver performs a linear minimum mean square error (LMMSE) estimation [7] to estimate the channels of the users using the T_t pilot symbols. During the remaining T_d symbols, data transmission occurs and the receiver uses the estimated channel gains to detect the data. Therefore the total block length for every user is $T = T_t + T_d$ symbol periods. We consider a block-fading scenario where the channel remains constant during one block and changes to an i.i.d. realization in the next block. Furthermore, each user transmits its pilot

¹The assumption of non-overlapping training sequences is often used in multiuser MAC systems [4], [5], in order to avoid interference between the pilot symbols of the users. With the non-overlapping training sequences, the base station can employ simple estimation methods to obtain accurate channel estimates, which result in a good capacity or error probability performance. The training overhead is relatively small in slow fading channels with a small number of MAC users, while it increases as the number of users increases.

Hamed Pezeshki and Behrouz Maham are with the School of Electrical and Computer Engineering, University of Tehran, Tehran 14395-515, Iran (e-mails: {h.pezeshki, bmaham}@ut.ac.ir).

Xiangyun Zhou is with the Research School of Engineering, The Australian National University, ACT 0200, Australia (e-mail: xiangyun.zhou@anu.edu.au).

and data symbols with power P_{t_k} and P_{d_k} , respectively. On the attacker side, the jammer also uses different jamming power, i.e., P_{wt_k} and P_{wd} , to jam the training symbols of user k and the data symbols of all the users, respectively.²

We consider the LMMSE estimator. For the channel of every user, we have $h_k = \hat{h}_k + \tilde{h}_k$, where \hat{h}_k and \tilde{h}_k are the estimated channel and channel estimation error of user k , respectively, and we have [7]

$$\sigma_{\hat{h}_k}^2 = \frac{\frac{P_{t_k}}{1+P_{wt_k}} T_{t_k}}{1 + \frac{P_{t_k}}{1+P_{wt_k}} T_{t_k}} \quad \text{and} \quad \sigma_{\tilde{h}_k}^2 = \frac{1}{1 + \frac{P_{t_k}}{1+P_{wt_k}} T_{t_k}} \quad (2)$$

where $\sigma_{\hat{h}_k}^2$ and $\sigma_{\tilde{h}_k}^2$ are the variances of \hat{h}_k and \tilde{h}_k , respectively.

III. PROBLEM FORMULATION

We consider a smart jamming design in an energy-constrained scenario and denote the average power budget of the jammer by P_w . Hence, we have $P_w T = \sum_{k=1}^K P_{wt_k} T_{t_k} + P_{wd} T_d$. We assume that the jammer allocates the ratio ζ_{t_k} and ζ_d of its total energy to jam the training signal of user k and the data symbols of all the users, respectively. Hence, for the jammer, we have

$$\zeta_{t_k} = \frac{P_{wt_k} T_{t_k}}{P_w T} \quad \text{and} \quad \zeta_d = \frac{P_{wd} T_d}{P_w T}. \quad (3)$$

Define $\zeta_t = \sum_{k=1}^K \zeta_{t_k}$, which is the ratio of the energy that the jammer allocates to the training phase. Then we have $\zeta_t + \zeta_d = 1$. In this letter, we look from the jammer's point of view and find the optimal values of $\{\zeta_{t_k}\}_{k \in \mathcal{K}}$ and ζ_d which minimize the achievable ergodic sum-rate, when the legitimate users' system parameters are known, i.e., for any given values of $\{P_{t_k}\}_{k \in \mathcal{K}}$, $\{P_{d_k}\}_{k \in \mathcal{K}}$ and $\{T_{t_k}\}_{k \in \mathcal{K}}$.

When the CSI at the receiver is noisy, the optimum input distribution and hence the exact expression for the ergodic sum-capacity are unknown. However, the maximum achievable sum-rate with Gaussian signalling is given by [5]

$$R = \frac{T - T_t}{T} \mathbb{E}_{\hat{h}_k} \left[\log_2 \left(1 + \frac{\sum_{k=1}^K \frac{P_{d_k}}{1+P_{wd}} |\hat{h}_k|^2}{1 + \sum_{k=1}^K \sigma_{\hat{h}_k}^2 \frac{P_{d_k}}{1+P_{wd}}} \right) \right] \quad (4)$$

where $\frac{T-T_t}{T}$ reflects the amount of time spent during the training phase and leads to the capacity loss. Now we further obtain an upper bound and a lower bound on R .

1) *Upper-Bound*: Considering the fact that $\log_2(1+x)$ is a concave function of x , we use Jensen's inequality to derive an upper bound on R . Hence, we have

$$\begin{aligned} R &\leq \frac{T - T_t}{T} \log_2 \left(1 + \frac{\mathbb{E}_{\hat{h}_k} \left\{ \sum_{k=1}^K \frac{P_{d_k}}{1+P_{wd}} |\hat{h}_k|^2 \right\}}{1 + \sum_{k=1}^K \sigma_{\hat{h}_k}^2 \frac{P_{d_k}}{1+P_{wd}}} \right) \\ &= \frac{T - T_t}{T} \log_2 (1 + \rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d)) = R_{UB} \end{aligned} \quad (5)$$

²We assume that the jammer has certain knowledge about the system it is attacking on, and hence it can infer the system parameters of the legitimate users through measurements [3].

where

$$\rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d) = \frac{\sum_{k=1}^K \frac{P_{d_k}}{1+P_{wd}} \sigma_{\hat{h}_k}^2}{1 + \sum_{k=1}^K \sigma_{\hat{h}_k}^2 \frac{P_{d_k}}{1+P_{wd}}}. \quad (6)$$

2) *Lower-Bound*: Define the vector $[x_1, \dots, x_K]$ of multiple variables. Then, $\log_2(1 + \sum_{k=1}^K a_k e^{x_k})$ is a convex function on \mathbb{R}^K for arbitrary $a_k > 0$ [8, Lemma 3]. Hence by applying Jensen's inequality in (4), we have

$$R \geq \frac{T_d}{T} \log_2 \left(1 + \sum_{k=1}^K \frac{\frac{P_{d_k}}{1+P_{wd}} \exp(\mathbb{E}\{\log[|\hat{h}_k|^2]\})}{1 + \sum_{k=1}^K \sigma_{\hat{h}_k}^2 \frac{P_{d_k}}{1+P_{wd}}} \right) = R_{LB}. \quad (7)$$

Following [8], we know that $\mathbb{E}\{\log[|\hat{h}_k|^2]\} = \log(\sigma_{\hat{h}_k}^2) + \psi(1) = \log(\sigma_{\hat{h}_k}^2) - \kappa$ where ψ is the psi function [9, Eq. (8.360)] and $\kappa \approx 0.577$ is the Euler's constant. Hence, we can derive a closed-form solution for R_{LB} , which is given by

$$R_{LB} = \frac{T - T_t}{T} \log_2 (1 + \rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d) \exp(-\kappa)). \quad (8)$$

We observe that the jamming strategy dependent term in both R_{UB} and R_{LB} is the same and given by $\rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d)$.

To improve the analytical tractability of the jammer design, we design the jamming energy allocation strategy to minimize both the upper and lower bounds on the maximum achievable sum-rate, instead of the exact sum-rate expression in (4). The solution obtained from this design is expected to have near-optimal performance in terms of minimizing the exact sum-rate. In order to minimize R_{UB} and R_{LB} , we must minimize $\rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d)$, since $\log_2(1+ax)$ is a continuous and increasing function of x with $a > 0$. By substituting $\sigma_{\hat{h}_k}^2$ and $\sigma_{\tilde{h}_k}^2$ from (2) into (6) and using (3), we have

$$\rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d) = \frac{\gamma(\zeta_d) \sum_{k=1}^K \alpha(\zeta_{t_k})}{1 + \gamma(\zeta_d) \sum_{k=1}^K \beta(\zeta_{t_k})} \quad (9)$$

where $\gamma(\zeta_d) = \frac{1}{1 + \zeta_d P_w T / T_d}$ and

$$\alpha(\zeta_{t_k}) = \frac{\frac{P_{d_k} P_{t_k} T_{t_k}}{1 + \zeta_{t_k} P_w T / T_{t_k}}}{1 + \frac{P_{t_k} T_{t_k}}{1 + \zeta_{t_k} P_w T / T_{t_k}}}, \quad \beta(\zeta_{t_k}) = \frac{P_{d_k}}{1 + \frac{P_{t_k} T_{t_k}}{1 + \zeta_{t_k} P_w T / T_{t_k}}}. \quad (10)$$

Thus, we have driven an expression which includes the system parameters of all the users and we use (9) as the objective function of the optimization problem in the succeeding section.

IV. OPTIMAL JAMMING POWER ALLOCATION

The optimal jamming energy allocation can be written as the following optimization problem:

$$\arg \min_{\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d} \rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d) \quad (11)$$

$$\text{s.t.} \quad \{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d \geq 0, \sum_{k=1}^K \zeta_{t_k} + \zeta_d = 1 \quad (12)$$

where $\rho(\{\zeta_{t_k}\}_{k \in \mathcal{K}}, \zeta_d)$ is given by (9). The following theorem presents the solution, i.e., $\{\zeta_{t_k}^*\}_{k \in \mathcal{K}}$ and ζ_d^* .

A. Main Result

Theorem 1: The optimal jamming energy allocation must satisfy the equations in (13)-(15), where (13) is shown at the bottom of the page³.

$$\zeta_d^* = \frac{1}{P_w T} \left(\frac{\sqrt{P_w T T_d \sum_{k=1}^K \alpha(\zeta_k^*)}}{\sqrt{\nu^*} \left(1 + \gamma(\zeta_d^*) \sum_{k=1}^K \beta(\zeta_k^*) \right)} - T_d \right)^+ \quad (14)$$

$$\sum_{k=1}^K \zeta_k^* + \zeta_d^* = 1 \quad (15)$$

We have a system of $K + 2$ non-linear equations and we can directly solve them to find the optimal values of $K + 2$ variables. If P_w is sufficiently high, all the calculated values of $\{\zeta_k^*\}_{k \in \mathcal{K}}$ and ζ_d^* will be positive. In this case, we can derive closed-form solutions for the optimal jamming energy allocation in terms of the training and data transmission parameters of all users, which is given as

$$\zeta_{t_k}^* = \frac{P_w T + T + \delta + T_d \sum_{i \in \mathcal{K}} P_{d_k} - \frac{1 + P_{t_k} T_{t_k}}{\sqrt{P_{d_k} P_{t_k}}} (2\eta)}{2P_w T \left(\frac{\eta}{T_{t_k} \sqrt{P_{d_k} P_{t_k}}} \right)}, \quad k \in \mathcal{K} \quad (16)$$

$$\zeta_d^* = \frac{1}{2} + \frac{T_t + \delta - T_d(1 + \sum_{i \in \mathcal{K}} P_{d_k})}{2P_w T} \quad (17)$$

where

$$\delta = \sum_{i \in \mathcal{K}} P_{t_i} T_{t_i}^2 \quad \text{and} \quad \eta = \sum_{i \in \mathcal{K}} T_{t_i} \sqrt{P_{d_i} P_{t_i}}. \quad (18)$$

Proof: It can be shown that the Hessian of the objective function in (9) is positive, so the problem is convex in $\{\zeta_k^*\}_{k \in \mathcal{K}}$ and ζ_d . Introducing Lagrange multipliers $\{\lambda_k^*\}_{k \in \mathcal{K}}$ and λ_d^* for the inequality constraints and ν^* for the equality constraint in (12), we obtain the KKT conditions as

$$\{\zeta_k^*\}_{k \in \mathcal{K}}, \zeta_d^* \geq 0, \quad \sum_{k=1}^K \zeta_k^* + \zeta_d^* = 1, \quad \{\lambda_k^*\}_{k \in \mathcal{K}}, \lambda_d^* \geq 0 \quad (19)$$

$$\lambda_k^* \zeta_k^* = 0, \quad k \in \mathcal{K}, \quad \lambda_d^* \zeta_d^* = 0 \quad (20)$$

$$- \frac{P_w T \gamma(\zeta_d^*) P_{d_k} P_{t_k} T_{t_k}^2 \left(1 + \gamma(\zeta_d^*) \sum_{k=1}^K P_{d_k} \right)}{\left(P_w \zeta_k^* T + T_{t_k} (1 + P_{t_k} T_{t_k}) \right)^2 \left(1 + \gamma(\zeta_d^*) \sum_{k=1}^K \beta(\zeta_k^*) \right)} - \lambda_k^* + \nu^* = 0, \quad k \in \mathcal{K} \quad (21)$$

$$- \frac{P_w T T_d \sum_{k=1}^K \alpha(\zeta_k^*)}{\left(P_w \zeta_d^* T + T_d \right)^2 \left(1 + \gamma(\zeta_d^*) \sum_{k=1}^K \beta(\zeta_k^*) \right)} - \lambda_d^* + \nu^* = 0. \quad (22)$$

³Here we employ the common notation, $(z)^+ = \max(0, z)$.

Note that $\{\lambda_k^*\}_{k \in \mathcal{K}}$ and λ_d^* act as slack variables in (21) and (22), hence they can be eliminated. If we solve (19)-(22), we get to the equations in (13)-(15).

If the calculated values of $\zeta_{t_i}^*$ and $\zeta_{t_j}^*$ are positive, we conclude from (13) that

$$\frac{P_{d_i} P_{t_i} T_{t_i}^2}{\left(P_w \zeta_{t_i}^* T + (P_{t_i} T_{t_i} + 1) T_{t_i} \right)^2} = \frac{P_{d_j} P_{t_j} T_{t_j}^2}{\left(P_w \zeta_{t_j}^* T + (P_{t_j} T_{t_j} + 1) T_{t_j} \right)^2}, \quad i, j \in \mathcal{K}. \quad (23)$$

As mentioned previously, for sufficiently high P_w , all the calculated values of $\{\zeta_k^*\}_{k \in \mathcal{K}}$ and ζ_d^* will be positive. In this case, we can calculate the values of $\{\zeta_{t_i}^*\}_{i \in \mathcal{K}, i \neq k}$ in terms of ζ_k^* by (23). By substituting $\alpha(\zeta_k^*)$ from (10) into (14) and using (23), we also calculate ζ_d^* in terms of ζ_k^* . Now $\{\zeta_{t_i}^*\}_{i \in \mathcal{K}, i \neq k}$ and ζ_d^* have been calculated in terms of ζ_k^* . If we substitute them into the equality constraint in (19), we get to the equations in (16) and (17). ■

B. Further Analysis

In the following, we consider various special cases to further analyse the impacts of different system parameters on the optimal jammer strategy.

Corollary 1: If $T_{t_k} = T_{t_j} \triangleq T_{t_c}$, $P_{t_k} = P_{t_j} \triangleq P_{t_c}$ and $P_{d_k} > P_{d_j}$, then $\zeta_{t_k}^* \geq \zeta_{t_j}^*$.

Proof: From (23) we have

$$\frac{P_{d_k}}{P_{d_j}} = \left(\frac{P_w \zeta_k^* T + (P_{t_c} T_{t_c} + 1) T_{t_c}}{P_w \zeta_j^* T + (P_{t_c} T_{t_c} + 1) T_{t_c}} \right)^2 > 1 \Rightarrow \zeta_k^* > \zeta_j^*. \quad (24)$$

and the equality holds when both of them equal zero. ■

Although the training parameters of the two users are the same, the optimal jammer allocates more power to jam the training symbols of the user with more data power, so that it can impair the channel estimate of that user more, which results in poorer data detection and lower data rate.

Corollary 2: If $T_{t_k} = T_{t_j} \triangleq T_{t_c}$, $P_{d_k} = P_{d_j} \triangleq P_{d_c}$ and $P_{t_k} > P_{t_j}$, then $\zeta_{t_k}^* \geq \zeta_{t_j}^*$.

Proof: From (23) we have

$$\frac{P_{t_k}}{P_{t_j}} = \left(\frac{P_w \zeta_k^* T - \sqrt{P_{t_k} P_{t_j}} + T_{t_c}}{P_w \zeta_j^* T - \sqrt{P_{t_k} P_{t_j}} + T_{t_c}} \right)^2 > 1 \Rightarrow \zeta_k^* > \zeta_j^*. \quad (25)$$

and the equality holds when both of them equal zero. ■

Hence, when the training duration and data power of two users are the same, the optimal jammer allocates more power to jam the training symbols of the user with larger training power to impair its channel estimate more.

$$\zeta_k^* = \frac{1}{P_w T} \left(\frac{\sqrt{P_w T \gamma(\zeta_d^*) P_{d_k} P_{t_k} T_{t_k}^2 \left(1 + \gamma(\zeta_d^*) \sum_{k=1}^K P_{d_k} \right)}}{\sqrt{\nu^*} \left(1 + \gamma(\zeta_d^*) \sum_{k=1}^K \beta(\zeta_k^*) \right)} - T_{t_k} (1 + P_{t_k} T_{t_k}) \right)^+, \quad k \in \mathcal{K} \quad (13)$$

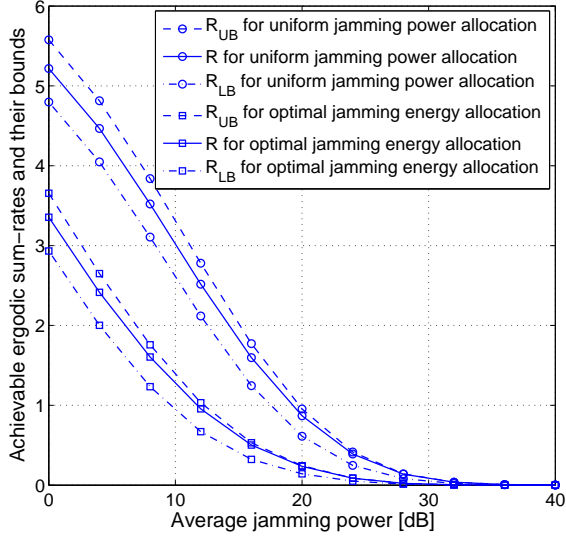


Fig. 1. Achievable ergodic sum-rates and their bounds versus the average jamming power P_w for a system of four users with a block length of $T = 100$ and training length of $T_t = 4$. The legitimate users' energy allocation is set to the optimal case for jamming-free systems.

Corollary 3: If $P_{t_k} = P_{t_j} \triangleq P_{t_c}$, $P_{d_k} = P_{d_j} \triangleq P_{d_c}$ and $T_{t_k} > T_{t_j}$, then $\zeta_{t_k}^* \geq \zeta_{t_j}^*$.

Proof: From (23) we have

$$\frac{T_{t_k}}{T_{t_j}} = \frac{P_w \zeta_{t_k}^* T - T_{t_k} T_{t_j} P_{t_c}}{P_w \zeta_{t_j}^* T - T_{t_k} T_{t_j} P_{t_c}} > 1 \Rightarrow \zeta_{t_k}^* > \zeta_{t_j}^*. \quad (26)$$

and the equality holds when both of them equal zero. ■

Hence, when the training and data power of two users are the same, the optimal jammer allocates more energy to jam the training symbols of the user with larger training duration, which is in line with our expectation.

Corollary 4: If $P_w \rightarrow \infty$, the optimal jamming energy allocation is given by

$$\zeta_{t_k}^* = \frac{T_{t_k} \sqrt{P_{t_k} P_{d_k}}}{2 \sum_{i=1}^K T_{t_i} \sqrt{P_{t_i} P_{d_i}}}, \quad \zeta_d^* = \frac{1}{2} \quad (27)$$

Proof: The proof is straightforward by the equations in (16) and (17). ■

V. NUMERICAL RESULTS AND DISCUSSION

In this section, we present numerical results on the optimal energy allocation of the smart jammer. We have considered four users with average power budgets 5, 10, 15 and 20 dB, respectively. Our model of the legitimate users is a special case of the system model in [5]. Hence, we have used the results of [5] to set the values of P_{t_k} and P_{d_k} which satisfy the given average power budget and maximize the achievable ergodic sum-rate in jamming-free systems. According to [5], the optimal training duration for each of the users equals one and hence the total training duration equals four.

Fig. 1 shows the performance gain of the optimal jammer over a jammer with uniform power allocation, i.e., $\zeta_{t_k} = T_{t_k}/T$ and $\zeta_d = T_d/T$. We plot R_{LB} , R and R_{UB} achieved by using the optimal energy allocation given by Theorem 1. We observe that the data rate degradation caused by the designed jammer is significant.

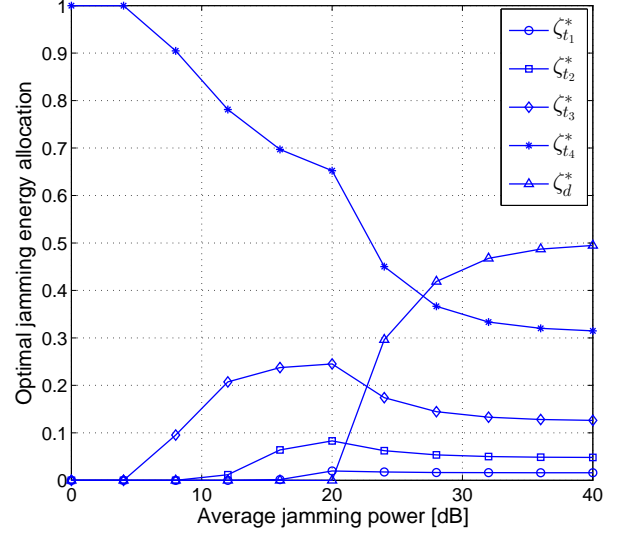


Fig. 2. Optimal jamming energy allocation versus the average jamming power P_w for a system of four users with a block length of $T = 100$ and training length of $T_t = 4$.

Fig. 2 illustrates the optimal jamming energy allocation versus the average jamming power budget P_w . For very small values of P_w , the optimal jammer allocates all its power to jam the training symbols of user 4, which has the largest power budget. As P_w increases, the jammer also allocates some power to jam the training signals of users 3, 2 and 1, respectively. Hence, as P_w increases, the training symbols of the users with more power budgets get jammed by the jammer sooner. We observe that when P_w is low, all power should be spent on jamming the training phase. If P_w exceeds 20 dB, the jammer starts jamming the data transmission phase and as P_w increases more, the optimal values of $\{\zeta_{t_k}\}_{k \in \mathcal{K}}$ and ζ_d approach the values given in Corollary 4. It is clear from Fig. 2 that $\zeta_{t_4}^* > \zeta_{t_3}^* > \zeta_{t_2}^* > \zeta_{t_1}^*$, which can be inferred from Corollary 1 and Corollary 2.

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